Review of Remote Detection for Natural Gas Transmission Pipeline Leaks

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Introduction

The detection of gas leaks represents a critical operation performed regularly by the gas industry to maintain the integrity and safety of its vast network of piping, both above and below the ground. Below-ground piping includes approximately 400,000 miles of transmission pipelines and 1.4 million miles of distribution piping, while above-ground piping is located mainly at about 750 gas processing plants and some 3000 compressor stations. Whether addressing above or below ground gas sources, leak surveying with state-of-the-art gas detectors can be a time-consuming operation of uncertain effectiveness.

For surveys of buried piping, state-of-the-art natural gas leak detectors employ a flame ionization detector (FID). A sampling pump in the unit continuously withdraws, or "sniffs," samples of the ambient air and delivers them through a sampling probe to the flame ionization sensor itself. The surveyor scans the ground, carrying the sampling probe barely above ground level. The probe must be brought fairly close to the leak vent to sample detectable quantities of gas. To find a leak quickly the surveyor must possess enough experience to know where to look. Complicating matters somewhat is the underground migration of leaking gas from buried pipes, causing the gas to reach the surface at some location often not apparent to the surveyor. Leak surveys with an FID can cover 8-10 miles per day in the man-portable mode, and slightly more in a vehicle-mounted mode. As an alternative to using an FID, low-flying aircraft are sometimes used to discern discolored vegetation caused by the gas leaks. This technique obviously cannot be used in areas without sufficient vegetation, such as the desert and steppe areas or during the winter.

As an example of an advanced leak-detection approach, Boreal Laser (Spruce Grove, Canada) uses an air-sampling laser-based gas sensor for pipeline monitoring that requires the aircraft to fly through the methane plume. Sampling the air significantly above the ground surface relies upon diffusion of the plume into the aircraft flight path. This technique is thus adversely affected by plume dilution and advection away from the pipe.

New Detection Technology

Based on these considerations, it would be desirable to develop a remote pipeline inspection instrument that could detect the leak remotely without physically sampling the air above the leak. Such a system might be implemented on an aircraft (Karapuzikov et al., 2000) or even a satellite (Davydov and Afonin, 1999). There are two alternatives for such remote sensing techniques: (1) active detection, which requires illuminating the scene with a radiation source, usually a laser, that is absorbed by the target gas, and (2) passive detection (also called thermal detection), which relies on radiative transfer due to a temperature and/or emissivity difference that usually exists between the background and the target cloud (see Fig. 1). While passive methods allow nearly unlimited range with a simple instrumental configuration, these methods rely upon a thermal flux between the plume and the ground surface below it. Active detection removes the thermal constraint, but requires a laser and a scattering surface behind the gas for generation of the signal. It also has a relatively lower operational range. In comparison to sampling probes, these remote detection technologies possess several advantages:

- They provide the potential for faster monitoring, and more frequent inspection for leaks (as caused by external infringements, material fatigue, etc.).
- By visualizing the entire leak rather than sampling a particular volume of air, they allow for more accurate pinpointing of the leak location, decreasing pipe excavation costs once the leak is detected.
- They allow a more complete and effective coverage of pipeline right-of-ways where leaks might migrate.
- They depend less on operator experience and judgment for leak detection.
- They provide the ability to monitor inaccessible, or "over the fence," areas.

Table 1 summarizes the critical differences between active and passive detection. The sensitivity of gas detectors is dependent on the product of the concentration of the target gas (ppm) and the thickness of gas plume (m), which is termed the CL product, also referred to as the path-integrated concentration. The noise equivalent concentration-length product (NECL), which is defined as the CL product producing a signal-to-noise ratio of unity, is the minimum CL that can be detected. Decreasing the NECL thus increases the sensitivity of the detection scheme. Fifteen years ago Flanigan (1986) analyzed the relationship between the NECL and the target distance for both active and passive detection systems. He found that passive systems have a sensitivity-advantage over active systems at ranges over 6 km. On the other hand, he also

concluded that active detection systems could be improved further relative to passive systems by decreasing laser power fluctuations and increasing the laser pulse repetition rate. Increasing the pulse repetition rate, which allows improved signal averaging and increased signal-to-noise ratios, was also recommended by Foy et al. (2001) for active laser-based detection of vegetation and geological features.

Active Detection

Background

Incident radiation
Backscattered radiation
CH_4
Incident radiation
Backscattered radiation

Passive Detection

CH_4
T_{plume}
Radiation to detector
Radiative transfer
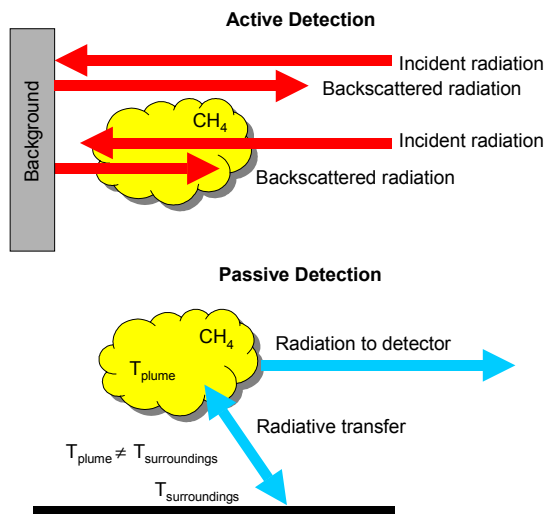$T_{plume} \neq T_{surroundings}$
$T_{surroundings}$

Fig. 1. Illustration of active and passive detection systems.

This review discusses passive and active techniques of gas leak detection, and the potential application of these techniques to transmission pipelines. As such, it will serve as a source for developing state-of-the-art sensor technology for the detection of transmission pipeline gas leaks.

Definition of Problem

The routine inspection of transmission pipelines poses additional challenges for gas leak detection because of the large standoff distances required for airborne or satellite platforms. Remote detection of these leaks will likely require sweeping over the area of interest to acquire an image of the methane concentration at the ground surface. For active detection, this can be accomplished by either dithering a laser beam back and forth across the field of view or by spreading the laser beam so that it encompasses the necessary field of view. Because a point detector can perhaps be used for the active system, further improving the design will require optimizing the aperture (Leeb et al., 1998) for improved speckle reduction (MacKerrow and Schmitt, 1997). For passive detection the image will require frequent acquisition of the field of view. Because of the speed of airborne and especially satellite travel, the acquisition must be performed at a rapid rate

to cover the required ground space within the area of interest.

The spatial distribution of gas within a plume from a pipeline leak is another important consideration in gas leak detection. Influential factors include: the pipe dimension, the internal pressure of the gas in the pipe, the size and characteristics of the leak, the amount of overburden or soil, the soil venting conditions, and the meteorological conditions in the vicinity of the leak. Soil venting is affected by such factors as the moisture content, the soil composition and compaction, and ground frost. Meteorological conditions include such factors as wind speed and direction, ambient air temperature and the atmospheric stability or degree of vertical mixing near the pipe. The distribution of gas within the plume will strongly influence the CL product that will be monitored by either an active or passive detection system. A variety of natural gas pipeline leak scenarios can be evaluated using published leak dispersion parameterizations. The three-dimensional spatial distribution of gas within the plume can be computed using these models and further analyzed using other software tools to determine the CL product of various look angles through the plume. These baseline leak rate and plume configuration data can be used in combination with estimated CL-product detection levels for the various candidate technologies to conduct a first-order assessment of the minimum detectable mass leak rate. Standoff distances and background methane levels can also be factored into such analyses to further assess technology performance.

Passive Detection Systems

Passive infrared detection systems have been developed to view chemical plumes, and several such imagers are offered commercially (e.g., Physical Sciences Inc., Andover, MA). One of the main advantages of passive techniques is that they do not require a background from which to scatter radiation. This is not an advantage for an airborne system, however, because the ground serves as a backscatter surface. In addition, since passive methods require a temperature/emissivity difference with the background, the detected gas will appear invisible at the temperature for which there is no net radiative heat transfer between the gas and the surroundings (Kulp et al., 1998a). Several schemes have been considered for passive methods to enhance the detection of natural gas. These include the following:

Filtering techniques: discrete bandpass cold filters (Althouse and Chang, 1994), a quantum ferroelectric hyperspectral imager (Birnbach and Vincent, 1999), and cold tunable etalon filters (Marinelli and Green, 1995)

Spectroscopic techniques: Frequency-heterodyning techniques (Simpson et al., 1997; Milligan et al., 1999; Smith et al., 1999), imaging-mode Michelson interferometers and Fourier transform techniques (Bennet, 1995; Polak et al., 1995), interferometry (Nguyên et al., 1995a,b), and gas-correlation spectroscopy (Sandstein et al., 1996, 2000; Ward and Zwick, 1975, Lee et al., 1985).

Background-interference techniques: Schlieren optics (Peale and Summers, 1996; Peale et al., 2000) and illumination gradients (Perciante et al., 2000)

Of these approaches, filtering techniques and spectroscopic techniques could potentially apply to the detection of transmission pipeline leaks; background interference techniques require a controlled background surface. However, all of these enhancements at best just reduce the noise from background radiation. Other sources of noise include shot noise, detector noise, and amplifier noise (Hobbs, 2000). As an example of a passive system, GasOptics (Lund, Sweden) currently markets a gas-correlation instrument for plant leakage measurements, and they report to be developing an airborne system. In addition to techniques based on passive gas detection, traditional thermography can detect secondary temperature differences due to the presence of a gas, and has been suggested as a technique for finding gas leaks. Thermographic techniques assume that neighboring surfaces have similar emissivities and interpret infrared signals as temperature variations. Some studies (Ljungberg et al., 1997; Aleev et al., 1993) have indicated that thermography could be more sensitive than techniques that are designed to detect the actual gas. However, thermographic techniques can provide ambiguous results, since surface albedo (the ratio of scattering to the sum of absorption and scattering) changes can be misinterpreted as temperature differences, resulting in false positive readings.

Active Detection Systems

Due to the development of laser sources emitting wavelengths in hydrocarbon absorption bands, active laser-based methods have recently been applied to the detection of methane. Many of these devices are based on point-detection methods, for which the laser return signal is collected on a single detector. These techniques can be extended to wide area coverage by implementing them with scanning optics. For example, SRI International (Menlo Park, CA) has developed a vehicle-mounted gas point-detection system with a scanning optical head. Point-detection methods include those based on gas correlation spectroscopy (Minato et al., 1998, 1999), where a laser emits radiation that is spectrally broader than the absorption feature. The

spectral components of the laser on and off the absorption feature are then separated to provide for a differential absorption measurement of the CL product. Pulsed differential absorption lidar systems have also been developed for remote point-detection of methane leakage (Ikuta et al., 1999; Prasad and Geiger, 1996). In addition, continuous-wave (cw) diode lasers with frequency modulation (FM) can be implemented into optical gas detection systems (Iseki et al., 2000). Millimeter-wave radar has also been used to detect airborne chemicals (Gopalsami and Raptis, 2001). However, its sensitivity depends on the dipole moment of the probed molecule. Because methane is not a polar molecule, natural gas leaks would not be easily detectable with radar-based techniques.

Laser Imaging Systems of Punta Gorda, FL, provides a commercial version of a gas imager based on backscatter absorption gas imaging (BAGI) using cw CO_2-laser illumination (McRae and Kulp, 1993). LaSen (Las Cruces, NM) has also developed a gas imager based on pulsed laser illumination. For backscattered imaging, cw imagers work by scanning both the laser and the detector field of view back and forth over the scene, while pulsed imagers work by flooding the scene, or a particular fraction of the scene, with laser radiation, taking a snapshot of the illuminated area. Based on the BAGI technique, Sandia National Laboratories (SNL) has developed a variety of active imaging systems for the detection of gas leaks. These imagers have encompassed both short-range ($\leq$20 m) systems on person-portable platforms (Goers et al., 2001) and long-range ($\leq$300 m) systems (Kulp et al., 1993) more suited to vehicle or airborne platforms. SNL has incorporated both cw lasers and pulsed lasers (Kulp et al., 1998b, Powers et al., 2000) into their imagers.

Future Directions

Detecting leaks in transmission pipelines poses a series of practical problems not often encountered in laboratory analyses of the techniques mentioned in this report. While systems exist for remote gas leak detection, they generally have not been designed for or implemented into airborne platforms. Studies to locate transmission pipeline leaks should address the detection limit in terms of the CL product for realistic measurement situations (typical ground albedo characteristics, atmospheric attenuation of the signal strength, movement of the instrument during measurement, etc.). Some such general studies have been implemented for imaging spectrometers (Nieke et al., 1999) and remote sensing satellites (Fiete, 1999; Fiete and Tantalo, 2001) but have not been extended to gas sensing.

For selection of the optimum technology, a quantitative assessment of the relative sensitivities of the different techniques is required. In particular, it is

necessary to determine the detection limits of the techniques for natural gas in the atmosphere. Such an analysis should include all major noise sources in the system, and incorporate experimental tests for comparison to the analytical study. Often this will require simply scaling the detection limits reported for different species to the methane absorption cross section. However, it may be more complicated to extend the analysis to the longer distances required for airborne detection. The troposphere has an approximate 1.5-ppm methane background, and long-range detection of a leak through this background may be problematic. To achieve a detectable return signal it may thus be necessary to tune the passive or active detection system to a weak absorption feature of methane (Ambrico et al., 2000).

In addition to a direct comparison of existing technologies, potential advanced or hybrid technologies should be considered for remote detection of natural gas. For example, it may be advantageous to couple active and passive systems (Harney, 1981) to acquire a passive image that is insensitive to the albedo of the scene.

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Table 1. Comparison of Active and Passive Detection Systems (modified from Harney, 1981).

Active Detection	Passive Detection	Implications and Limitations
Requires a radiative source absorbed by the target gas	Requires a temperature difference between the target gas and the surroundings	For active imaging, the detection limit improves with increasing radiative-source power. For passive imaging, the detection limit improves with an increasing temperature/emissivity difference between the target gas and the surroundings. Quantitative measurements of the CL product cannot be made without accounting for variations in radiative-source power (for active detection) or temperature/emissivity differences (for passive detection).
Detection of gas requires a reflective background surface	Detection of gas does not require a background surface	For active detection the radiation source must have a hard target from which it will scatter and return to the detector. For pipeline monitoring, the ground surface acts as the backscatter target, so this is not a critical issue for detecting leaks from an airborne system.
Contrast between gas and surroundings is sensitive to reflectivity differences	Contrast between gas and surroundings is sensitive to temperature and emissivity differences	Reflectivity differences can be accounted for in active detection by dual-wavelength detection, wherein the effect of the background can be subtracted from the image (Powers et al., 2000). However, the dynamic range of the instrument is often limited by this variation of the background reflectivity. We are not aware of a study that has fully addressed the effect of temperature and emissivity differences on passive gas-sensing techniques.
Speckle patterns induce noise	Signal is speckle-free	Speckle is the interference pattern that results from a *coherent* radiation source striking a hard target. The term coherent refers to how well the different parts of an electromagnetic field stay in phase with each other (Hobbs, 2000). A laser is generally a highly coherent source, whereas thermal radiation is incoherent. Speckle is a source of noise in a laser-based backscatter measurement, since the intensity of the return signal depends on the portion of the interference pattern collected by the detector. Speckle is not present in a passive measurement.
Gas detection is sensitive to target glints (strong specular reflections)	Gas detection is insensitive to target glints	Strong specular reflections result in large reflectivity differences between neighboring acquisition points. This can mask the absorption of the gas by saturating the detector and limiting the dynamic range of the measurement.
Range analysis is possible	Multispectral analysis is possible	Range analysis (in the case of active detection) allows the instrument to account for changes in the signal due to the varying distance to the target. Multispectral analysis (in the case of passive detection) allows a comparison of spectral bands that are either in or out of the absorption band of the target gas.
Limited effective range (satellite platform difficult)	Practically unlimited operational range (satellite platform possible)	The sensitivity of an active system decreases as the square of the distance to the hard target, which likely limits the effective range to low-flying aircraft (<1000 m). A passive system does not have this limitation.